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ELECTROWEAK PHYSICS AT THE TEVATRON RUN2: W,Z,$W\gamma$,$Z\gamma$ AND WW PRODUCTION.

S.CABRERA, ON BEHALF OF THE CDF AND DØ COLLABORATIONS.
Department of Physics, Box 90305, Duke University, Durham, NC 27708-0305, USA,
E-mail: cabrera@fnal.gov

The Run II CDF and DØ experiments have measured the inclusive W and Z cross sections with $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV using leptonic modes: $\sigma(p\bar{p}\to Z)\times BR(Z\to\ell^+\ell^-)$ and $\sigma(p\bar{p}\to W)\times BR(W\to\ell\nu)$. These measurements are in good agreement with the NNLO theoretical predictions. The production cross section of several diboson processes: $p\bar{p}\to W\gamma, Z\gamma, WW$ have been measured using W and Z leptonic modes with electrons and muons, establishing the framework to study the anomalous triple gauge couplings at the Tevatron Run 2.

1 Introduction.

Nowadays, the Tevatron collider at Fermilab is operating beams of 980 GeV, with 36 p and $\bar{p}$ bunches and 396 ns between bunch crossing. The Tevatron has delivered about 450 pb^{-1} up until April 2004. The upgraded CDF [1,2] and DØ [2] detectors have a great performace with a data taking efficiency better than 80%.

CDF has a new tracking system for Run2 within the existing 1.4 magnetic field: a new silicon microstrip detector with a coverage up to $|\eta|\sim$ 2 and a new drift chamber up to $|\eta|\sim$1. DØ has also new central tracking detectors: a silicon microstrip detector and a scintillating-fiber tracker, both located within a new 2 T superconducting solenoidal magnet. The hermetic DØ Run 1 central and two endcaps calorimeters remain unchanged but they incorporate new readout electronics and new central and forward preshower detectors.

2 Results on single boson production.

After the major upgrades of both collider detectors the inclusive W and Z cross section measurements have been crucial in the understanding of the detector performance, specially lepton trigger and lepton identification efficiencies. These measurements are the starting point of many other measurements since W and Z production are important backgrounds for diboson, top, Higgs and other non-SM processes at the Tevatron. In the particular case of the single W production process, the current level of precision in both the NNLO calculation and the experimental results (see (a) and (c) in Table 1) suggests this process could be a good candidate to provide luminosity normalization.

2.1 $Z\to\ell^+\ell^-$ and $W\to\ell\nu$ inclusive cross sections.

The data samples for the W and Z inclusive analysis (see Table 1) have been taken with high pt electron and muon triggers, except the analysis (b), where the trigger

Channel	η_{lepton}	$L(pb^{-1})$	N_{cand}	B (%)	A$\times\epsilon$ (%)	$\sigma \cdot Br$ (pb)
(a) $W\to e\nu$ CDF	$\lvert\eta\rvert < 1$	72	37584	4.4	17.9	2780$\pm$14$\pm$60$\pm$166
(b) $W\to e\nu$ CDF	$1.1 < \lvert\eta\rvert < 2.8$	64	10461	8.7	5.2	2874$\pm$34$\pm$167$\pm$172
(c) $W\to \mu\nu$ CDF	$\lvert\eta\rvert < 1$	72	31722	9.4	14.4	2768$\pm$16$\pm$64$\pm$166
(d) $W\to \tau\nu$ CDF	$\lvert\eta\rvert < 1$	72	2342	26.0	0.9	2620$\pm$70$\pm$210$\pm$160
(e) $W\to e\nu$ DO	$\lvert\eta\rvert < 1$	41	27400	5	18.4	2844$\pm$21$\pm$128$\pm$167
(f) $W\to \mu\nu$ DO	$\lvert\eta\rvert < 1.8$	17.3	8305	11.8	13.2	3266$\pm$128$\pm$100$\pm$322
$\sigma(p\bar{p}\to W)\times BR(W\to\ell\nu) = 2687\pm40$ pb $\ell : e,\mu$ NNLOtheory **[3]**						
(a) and (c): $\sigma(p\bar{p}\to W)\times BR(W\to\ell\nu) = 2775\pm10_{stat}\pm53_{syst}\pm167_{lum}\ pb$ **[5]**						
(g) $Z\to ee$ CDF	$1^{st}(2^{nd})e : \lvert\eta\rvert < 1(2.8)$	72	4242	1.5	22.7	255.8$\pm$3.9$\pm$5.5$\pm$15.0
(h) $Z\to \mu\mu$ CDF	$\lvert\eta\rvert < 1$	72	1785	0.7	9.9	248.0$\pm$5.9$\pm$7.6$\pm$15.0
(i) $Z\to ee$ DO	$\lvert\eta\rvert < 1.1$	41.6	1139	-	9.3	275.2$\pm$9.0$\pm$9.0$\pm$28.
(j) $Z\to \mu\mu$ DO	$\lvert\eta\rvert < 1.8$	117	6126	0.5	16.4	261.8$\pm$5.0$\pm$8.9$\pm$26.2
$\sigma(p\bar{p}\to Z/\gamma^*\to\ell^+\ell^-) = 250.5\pm3.8$ pb $\ell : e,\mu$ NNLOtheory **[3]**						
(e) and (f) $\sigma(p\bar{p}\to Z\to\ell^+\ell^-) = 254.9\pm3.3_{stat}\pm4.6_{syst}\pm15.2_{lum}\ pb$ **[5]**						

Table 1. Summary of inclusive W and Z cross section measurements, all in great agreement with the NNLO theoretical predictions [3].The sequence of errors is: stat, syst, lum.

selects a plug electron and $\not\!\!E_T$ and the analysis (d), that uses a new dedicated trigger that filters events with a hadronic tau decay and large $\not\!\!E_T$. For details on these analysis see for instance previous proceedings on the subject [4].

It is worth to report the CDF updates (a),(c) and (g), with systematic uncertainties greatly reduced mainly due to a better understanding of the material description in the detector simulation. The new drift chamber together with the unchanged Run 1 calorimeter provides electron identification in the central part of the detector.

The new CDF result (b) uses the new end-plug calorimeters and the extended silicon coverage that provide electron identification in the range $1.1 < |\eta| < 2.8$.A new Run II result is the CDF W$\to$ $\tau\nu$ cross section measurement (result (d) in Table 1).

The most important updated DØ result is (j) (see Table 1 and left plot in figure 1) and exploits the excellent upgrade of the DØ muon system, that consists of three large toroid magnets (one central and two forward) of 1.8 T and three layers of muon detectors, upgraded scintillator counters and drift chambers, one layer before and two layers after the magnets. Both (i) and (j) DØ results correct from the cross section measured in the region of invariant mass $M_{\mu\mu} > 30$ GeV/c^2 ($70 < M_{ee} < 110$ GeV/c^2) to the pure Z propagator with MC factors 0.983$\pm$0.004 (0.786$\pm$0.013) respectively. Both (g) and (h) CDF analyses measured the cross section in the region of invariant mass $66 < M_{ee} < 116$ GeV/c^2, being the MC correction factor 1.004 to account for the invariant mass cut and the γ^* component.

2.2 Lepton universality and indirect measurement of $\Gamma(W)$

CDF has tested the e-μ universality using W decays through the ratio of the W cross sections. No sign of non-universality was found, therefore the measurements (a) and (c), (e) and (f), are combined taking into account correlated uncertainties. From the measured ratio $R = \sigma(W)\times BR(W\to\ell\nu)/\sigma(Z)\times BR(Z\to\ell^+\ell^-) = 10.92\pm0.15_{stat}\pm0.14_{syst}$ and using the theoretical value of the width $\Gamma(W\to\ell\nu) = 226.4\pm0.3$ MeV an indirect measurement of the W boson total width can be extracted: $\Gamma_W^{tot} = 2079\pm41$ MeV, in agreement with the SM value: 2092.1$\pm$2.5 MeV (see reference [5]).

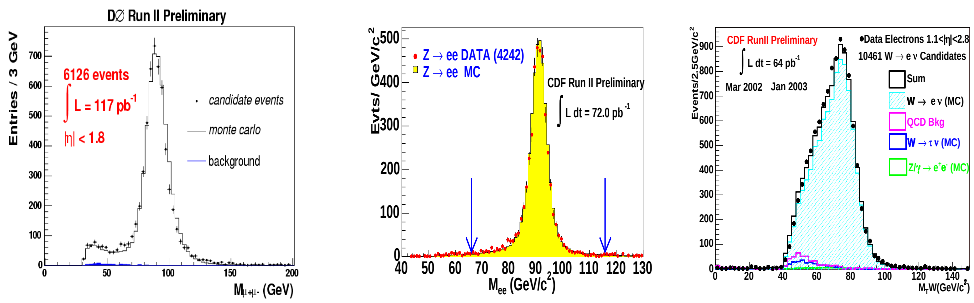

Figure 1. Dilepton invariant mass $M_{\ell\ell}$ for the analysis $Z\rightarrow\mu^+\mu^-$ DØ (left) and $Z\rightarrow e^+e^-$ CDF (middle).Transverse mass distribution $M_T = \sqrt{E_T \not{E}_T - (E_x \not{E}_{T,x} + E_y \not{E}_{T,y})}$ for the analysis W$\rightarrow e\nu$ CDF (right).

3 Results on diboson production

Diboson production at the Tevatron is the probe to study the anomalous triple gauge couplings: $W\gamma$ $(WW\gamma)$, $Z\gamma$ $(ZZ\gamma)$ and WW ($WW\gamma$ and WWZ) [6].

3.1 $W\gamma$ and $Z\gamma$.

The CDF analysis [7] selects W and Z using e and μ decay channels following the criteria of [5] and then at least one isolated photon with $E_T^\gamma > 7$ GeV in the central part of the detector $|\eta_\gamma|$ <1.1 and separated from the lepton e or μ with $\Delta R(\ell,\gamma)$ >0.7 to reduce the inner bremmstrahlung component (see figures 3.1). Additional requirements are: $M_T(l,\nu) < 120\ GeV/c^2$ and $M_{\ell\ell} > 40\ GeV/c^2$ $(\ell : e,\mu)$ for Wγ and Zγ candidates respectively.

The main background affecting both Wγ and Zγ processes are $W\rightarrow\ell\nu$ where one jet is *faking* a photon. The reason for that is predominantly high energy π^0 and η meson decaying into photons. These background is determined by applying a data driven jet$\rightarrow$ fake rate to the W and Z events. The jet$\rightarrow$ fake rate is evaluated using high statistics jet triggered data, and taking into account the real γ content in these jet data with techniques that exploit the shower profile information and the hit rate measured in the preshower detector. Other contributing backgrounds to the $W\gamma$ process are $W\gamma\rightarrow\tau\nu_\tau\gamma\rightarrow\ell\nu_\ell\nu_\tau\nu_\tau\gamma$ and $Z\gamma\rightarrow\ell^+\ell^-\gamma$ where one lepton is undetected resulting in high observed $\not{E}_T$. They are purely MC driven.

The kinematic properties of the observed $W\gamma$ candidates are in excellent agreement with the MC expectations for signal plus predicted background (see figure 2). High values of the cluster transverse mass $M_T(l\gamma,\not{E}_T\,)$, defined as: $M_T^2(l\gamma,\not{E}_T\,) = [\sqrt{M_{\ell\gamma}^2 + |\mathbf{p}_{T\gamma} + \mathbf{p}_{T\ell}|^2} + \not{E}_T\,]^2 - |\mathbf{p}_{T\gamma} + \mathbf{p}_{T\ell} + \not{E}_T\,|^2$ allow to enhance the s-channel, probe to test anomalous triple gauge couplings.

The DØ Wγ analysis follows the same strategy as the CDF analysis but selects the isolated photon with $E_T^\gamma > 7$ GeV. The results from both experiments are reported in Table 2 for the individual electron and muon channels. The combined results are in good agreement with the NLO theory prediction [8]:

	$W\gamma\rightarrow e\nu\gamma$		$W\gamma\rightarrow\mu\nu\gamma$	
	CDF	DØ	CDF	DØ
Luminosity	202	162±10.5	95.0±1.46 ±3.96	82.0±5.3
Signal	85.51±1.49± 4.45	55±17	41.12±0.39± 6.52	30±13
Signal + Bkgrd	119.54±1.51±9.57	142±17	136.1±1.51±7.63±6.88	67±13
Observed	131	146	128	77
Cross section (pb)	21.9±2.6±2.2±1.3	17.8±3.6±5.3±1.1	17.6±2.3±1.6±1.1	22.0±4.2±7.3±1.4

Table 2. $W\gamma$ analysis results from CDF and DØ experiments in the electron and muon channels respectively. The sequence of errors is: stat, syst, lum.

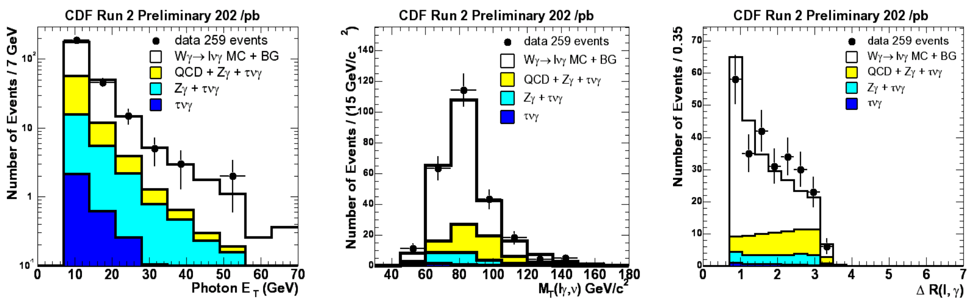

Figure 2. E_T^γ, $M_T(l\gamma, \not{E}_T)$ and $\Delta R(\ell,\gamma)$ for CDF Wγ candidates.

- CDF: $\sigma{\cdot}BR(p\bar{p}{\rightarrow}W\gamma{\rightarrow}\ell\nu_\ell\gamma) = 19.7{\pm}1.7_{stat}{\pm}2.0_{sys}{\pm}1.1_{lum}$ pb versus $\sigma{\cdot}BR(p\bar{p}{\rightarrow}W\gamma{\rightarrow}\ell\nu_\ell\gamma)_{NLO}$=19.3±1.3 pb for $E_T^\gamma > 7\ GeV$.

- CDF: $\sigma(p\bar{p}{\rightarrow}Z\gamma{\rightarrow}\ell^+\ell^-\gamma)_{NLO} = 5.3{\pm}0.6_{stat}{\pm}0.3_{syst}{\pm}0.3_{lum}$ pb versus $\sigma(p\bar{p}{\rightarrow}Z\gamma{\rightarrow}\ell^+\ell^-\gamma)_{NLO}$=5.4±0.3 pb for $E_T^\gamma > 7\ GeV$.

- DØ $\sigma(p\bar{p}{\rightarrow}W\gamma{\rightarrow}\ell\nu_\ell\gamma) = 19.3{\pm}2.7_{stat}{\pm}6.1_{syst}{\pm}1.2_{lum.}$ pb versus $\sigma(p\bar{p}{\rightarrow}W\gamma{\rightarrow}\ell\nu_\ell\gamma)_{NLO}$=16.4±0.4 pb for $E_T^\gamma > 8\ GeV$.

3.2 $WW{\rightarrow}\ell\nu\ell\nu$

The W^+W^- production cross section in the dilepton channel has been measured using a data sample of 197 pb^{-1} by CDF. The experimental signature consists of two oppositely charged high Pt leptons, high $\not{E}_T$ due to the presence of neutrinos and zero or low jet multiplicity due to initial and final-state radiation. The main backgrounds are Drell-Yan ($q\bar{q} \rightarrow Z/\gamma^\star \rightarrow \ell^+\ell^-$), $W \rightarrow \ell\nu + jets$ where a jet is misidentified as a lepton and $W+\gamma$ where a photon is falsely reconstructed as a lepton candidate, top pair production in the dilepton channel, $t\bar{t}{\rightarrow}WbW\bar{b}{\rightarrow}\bar{\ell}\nu_\ell b\ell'\bar{\nu}_{\ell'}\bar{b}$, and other heavy diboson production WZ and ZZ. Two measurements have been performed using two different experimental techniques. The *dilepton* analysis selects two well detected leptons, e or μ. This technique provides a high S/B ratio 2.5 and allows to classify final dileptons in three channels: ee, $\mu\mu$ and $e\mu$ accepting also leptonic decays of τ leptons. The *lepton plus track* analysis identifies the first lepton as e or μ with similar criteria than the *dilepton* analysis however the second lepton is an isolated track with $p_T >$ 20GeV/c in the range η <1. This technique

CDF	*l+track*	*dilepton*
Luminosity	~200	~200
Signal	16.3±0.4 $_{only\ stat}$	11.3±1.3
Signal+Bkgrd	31.5±1.0 $_{only\ stat}$	16.1±1.6
Observed	39	17
Cross section (pb)	19.4±5.1±3.5±1.2	$14.3^{+5.6}_{-4.9}$±1.6±0.9
$\sigma(p\bar{p}\to WW)_{NLO} = 12.5\pm0.8$ pb [10]		

Table 3. CDF results on WW production cross section. The sequence of errors is: stat, syst, lum.

provides high acceptance and sensitivity to hadronic τ decays.

Both analyses require $\not{E}_T > 25$ GeV. [a] In the range $25 < \not{E}_T < 50$ GeV both techniques take care of instrumental contributions to the $\not{E}_T$ due to mismeasured leptons or jets using topological cuts. The *dilepton* technique requires a minimum azimutal separation $\delta\phi > 20^0$ between the $\not{E}_T$ and the closest lepton or jet momentum. The ***lepton plus track*** technique corrects the $\not{E}_T$ for those lepton track candidates with $E_T^{3\times3}/p_T < 0.7$ [b]. Events with the $\not{E}_T$ direction within 5^0 around the track lepton candidate are rejected. A high $\not{E}_T$ significance requirement helps to improve the signal to background ratio by rejecting those backgrounds with instrumental contributions to the $\not{E}_T$, mainly Drell-Yan. The *dilepton* analysis requires $\not{E}_T{}^{Sig} > 3$ [c] in the region of dilepton invariant mass $76 < M_{\ell\ell} < 106$ for dilepton final states ee and $\mu\mu$, while the ***lepton plus track*** requires $\not{E}_T{}^{Sig} > 5.5$ [d] for all dilepton invariant masses.

Both analyses build jets using a cone algorithm with fixed size 0.4 and classify all events in jet multiplicity bins. The *dilepton* (*lepton+track*) analysis selects high E_T jets by demanding $E_T > 15(20)$ GeV/c^2 in the region $|\eta| < 2.5(2)$. In order to reduce the $t\bar{t}\to$***dileptons*** both analyses veto events with high jet multiplicity. In particular, the *dilepton* analysis veto events with jets and the *lepton+track* uses events with zero and one jet to extract the cross section measurement.

The dominant background in both analysis is $W\to\ell\nu$ with one jet *faking* the signature of one lepton. Its evaluation is purely data driven: a rate or *faking* probability has been measured using jet triggered data and it has been applied accordingly in the kinematic selection to the $W\to\ell\nu$ data sample. The *lepton+track* Drell-Yan background estimate is mainly data driven. The remaining background estimates are Monte Carlo based.

Both results are in agreement with the NLO theory prediction within the current accuracy (see Table 3).

[a] The vector sum $\not{E}_T$ is corrected for the selected muon momenta undetected in the calorimeter.
[b] $E^{3\times3}$ is the transvers energy in a 3×3 block of calorimeter towers having the central one intersected by the lepton track candidate
[c] $\not{E}_T{}^{Sig} = \not{E}_T/\sqrt{\Sigma E_T}$ where ΣE_T is the scalar sum tower by tower of the raw energy measured in the calorimeter.
[d] $\not{E}_T{}^{Sig} = \not{E}_T/\sqrt{\Sigma E_T}$ where ΣE_T is the sum of the corrected E_T of the identified lepton and high Et jets jets

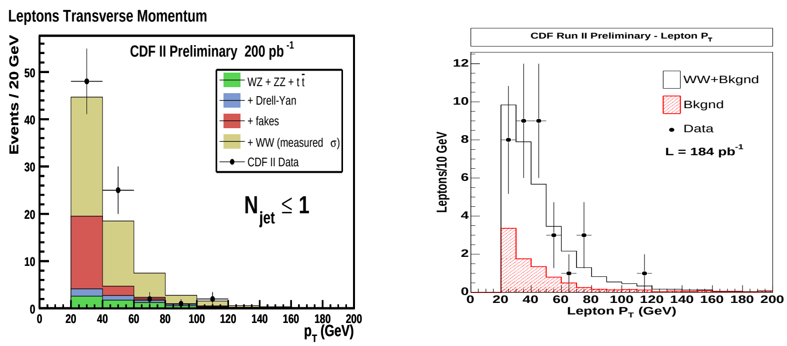

Figure 3. Lepton Pt distribution for WW candidates in the *lepton+track* analysis (left) and *dilepton* analysis (right). This distribution will be use to extract limits on TGC couplings.

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